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Temperature dependence of photoluminescence from Mg-doped $In_{0.5}Ga_{0.5}P$ grown by liquid-phase epitaxy

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The temperature dependence of photoluminescence from the Mg-doped $In_{0.5}Ga_{0.5}P$ layers on (100) GaAs substrates grown by liquid-phase epitaxy has been studied. At low temperature, the spectra show only two major emission peaks involving intrinsic recombination and conduction–band-to-acceptor transition. The intrinsic recombination dominates in the doping concentration range studied (1.0×10^{17}–7.0×10^{18} cm^{-3}) above 60 K. Below 50 K, these two peaks merged with each other when the doping concentration is higher than 1×10^{18} cm^{-3}. The temperature dependence of band gap in $In_{0.5}Ga_{0.5}P$ layers determined from the photoluminescence peak energy varies as $1.976 - [7.5\times10^{-4}T^2/(T+500)]$ eV. For the moderately doped concentration ($p < 1.4\times10^{18}$ cm^{-3}), the Mg acceptor ionization energy obtained from 50-K photoluminescent spectra is in the range from 37 to 40 meV.

I. INTRODUCTION

$In_{1-x}Ga_xP$ ternary compound offers the possibility of direct recombination luminescence up to photon energy of approximately 2.2 eV at 300 K and was predicted to be a highly efficient luminescence material,[1] providing an opportunity for the fabrication of visible light-emitting devices. Especially, with $x\sim0.5$, it can be lattice matched to GaAs, and thus has attracted much attention for the fabrication of red light-emitting devices.[2–5]

Mg and Zn are well known *p*-type dopants in GaAs and AlGaAs layers grown by liquid-phase epitaxy (LPE). Mg is expected to be more attractive than Zn as a *p*-type dopant in GaAs and related III-V compounds because the diffusion coefficient of Mg is about 10^3 times lower than that of Zn in GaAs.[6,7] Zn has been shown to migrate in AlGaAs at low temperature and produce compositional disorder at the AlGaAs-GaAs interface.[8] Recently, remarkable improvement in Mg doping efficiency, compared with that for Zn, has been observed for $(Al_xGa_{1-x})_{0.5}In_{0.5}P$, grown by metalorganic chemical vapor deposition (MOCVD), especially for a high aluminum composition layers.[9] Suzuki *et al.* reported the low-temperature photoluminescence (PL) properties of Mg-doped $In_{0.5}Ga_{0.5}P$ grown by MOCVD with different hole concentrations.[10] Chang *et al.* reported the doping properties of Mg in $In_{0.5}Ga_{0.5}P$ layers grown by LPE.[11] But there is no detailed report on the temperature dependence of luminescent properties of Mg-doped InGaP material or devices.

II. EXPERIMENT

This article reports the temperature dependence of photoluminescence of Mg-doped $In_{0.5}Ga_{0.5}P$ layers with various doping concentrations.

The Mg-doped $In_{0.5}Ga_{0.5}P$ epitaxial layers used for this study were grown on undoped semi-insulating GaAs substrates with a horizontal sliding LPE system. The growth temperature, the initial supercooling, and the cooling rate were 785 °C, 12 °C, and 0.3 °C/min, respectively. The thickness of the layers during a growth period of 17 min was 8–10 μm. Details of the LPE growth was described in Ref. 5.

The PL measurements were made using argon laser excitation (4880-Å line) with an average power density of ~5 W/cm^2 and a spot size of ~1 mm in diameter. The emission spectra were analyzed by a 1-m spectrometer and detected with a silicon pin photodetector. The samples were mounted on a holder inside a cryostat and the temperature was varied and controlled by a thermalfoil heater wound near the holder and detected by a Pt temperature sensor.

III. RESULTS AND DISCUSSIONS

Table I illustrates some of the electrical and optical properties at room temperature of the undoped and Mg-doped $In_{0.5}Ga_{0.5}P$ samples used for this investigation. An undoped $In_{0.5}Ga_{0.5}P$ sample with background concentration of 4×10^{16} cm^{-3} was used as a reference for the PL measurements. The fact that the room-temperature PL full width at half maximum (FWHM) of the four Mg-doped samples broadens as the carrier concentration increased is due to the evolution of the impurity levels into a band of states.

The PL spectra at 50 K of all the samples illustrated in Table I are shown in Fig. 1. These spectra are normalized to the same main peak intensity. Except for the undoped and most heavily doped samples No. 1 and No. 5, respectively, as shown in Figs. 1(a) and 1(e), all other samples exhibit three peaks denoted as A, B, and C. Peak A with the narrowest FWHM and the highest photon energy as shown in Fig. 1(a) of the undoped sample is corresponding to band-to-band (intrinsic) transition. The lower-energy peak B, the dominant transition process at temperature lower than 60 K, is due to the transition of band to acceptor level (BA). As shown in Fig. 1(b) with a hole concentration of 1.0×10^{17} cm^{-3}, its position is 38 meV below

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TABLE I. 300-K electrical and optical properties of the Mg-doped $In_{0.5}Ga_{0.5}P$ samples used in this study.

Sample No.	n or p ($\times 10^{17}$ cm^{-3})	Mobility (cm^2/V s)	PL peak energy (eV)	PL FWHM (meV)	PL intensity (AU)
1	undoped 0.4(n)	1300	1.890	36.5	1.8
2	1.0(p)	65	1.889	41.2	2.1
3	5.1(p)	52	1.890	45.0	4.5
4	14 (p)	41	1.880	59.5	3.8
5	70 (p)	29	1.885	75.5	0.6

peak A and moves closer to peak A with increasing hole concentration. Since the relative intensity of peak B to peak A increases with hole concentration, it confirms that peak B is definitely associated with the Mg acceptor level. The weak peak C located at $\sim$50 meV below peak B is believed to be the phonon replica of peak B. As the hole concentration is higher than $\sim 1\times 10^{18}$ cm^{-3}, these two peaks A and B merged with each other and is not distinguished even at 16 K. This is due to the evolution of acceptor impurity levels into a band and merging with the valence band.

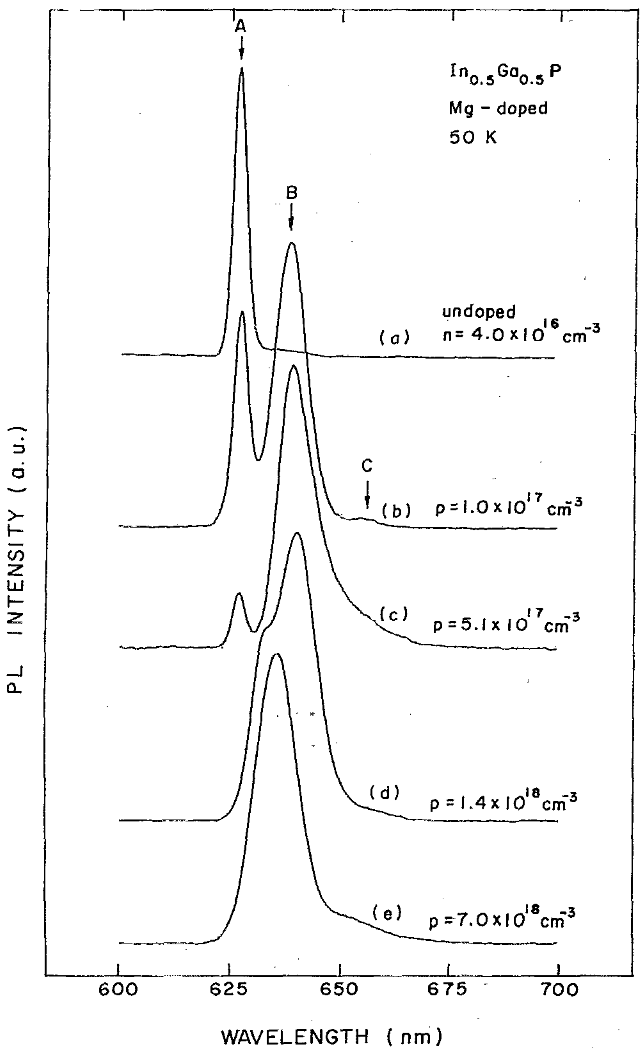

FIG. 1. 50-K PL spectra of Mg-doped $In_{0.5}Ga_{0.5}P$ layers grown on GaAs with a carrier concentration of (a) $n = 4.0 \times 10^{16}$ cm^{-3} (undoped), (b) $p = 1.0 \times 10^{17}$ cm^{-3}, (c) $p = 5.1 \times 10^{17}$ cm^{-3}, (d) $p = 1.4 \times 10^{18}$ cm^{-3}, and (e) $p = 7.0 \times 10^{18}$ cm^{-3}. The spectra are normalized to the same main peak intensity.

From this BA transition of peak B, the ionization energy of the Mg acceptor, E_A, can be estimated from the photon energy of peak B, $h\nu_B$, and Eg using Eagles equation:[12]

$$E_A = E_g - h\nu_B + \tfrac{1}{2}kT,$$

where E_g is the band-gap energy of $In_{0.5}Ga_{0.5}P$ and $h\nu_B$ is the peak energy of the Mg acceptor. The thermal-energy correction term $\frac{1}{2}\,kT$ adds about 2 meV to the term of $(E_g - h\nu_B)$ at 50 K. The ionization energy of Mg acceptor in the lightly doped $In_{0.5}Ga_{0.5}P$ is thus calculated as 37–40 meV at 50 K.

Figure 2(a) presents the temperature dependence (T=16–300 K) of the emission peak of sample No. 2 with a hole concentration of 1×10^{17} cm^{-3}. Peak B is the dominant recombination process at temperature below 60 K. As the temperature is increased, the intensity of this peak gradually decreased while that of peak A gradually increased. Above 130 K, the emission of peak B becomes negligibly weak. The decreasing of relative intensity of peak B with increasing temperature is due to the thermal release of holes from acceptor sites.

The PL spectra of sample No. 4 with a hole concentration of 1.4×10^{18} cm^{-3} is shown in Fig. 2(b). At 16 K, only peaks B and C are observed and it can be explained as the increase of transition probability due to higher hole population in the acceptor level. It is relevant to note in Table I that the PL intensity at 300 K reaches its maximum in the range from 5×10^{17} to 1.4×10^{18} cm^{-3} and then drops quickly as the hole concentration is further increased. There may be relatively deep centers formed at high Mg-doped concentrations to lower the radiative efficiency as in the case of heavily Zn-doped $In_{0.5}Ga_{0.5}P$ layers.[13–15]

Figure 3 shows the variation of the photon energies of the peaks A and B as a function of temperature for sample No. 2 with PL spectra shown in Fig. 2(a). The temperature dependence of the band gap in this figure can be expressed as the Varshni equation:[16]

$$Eg(T) = Eg(0) - \alpha T^2/(T+\beta),$$

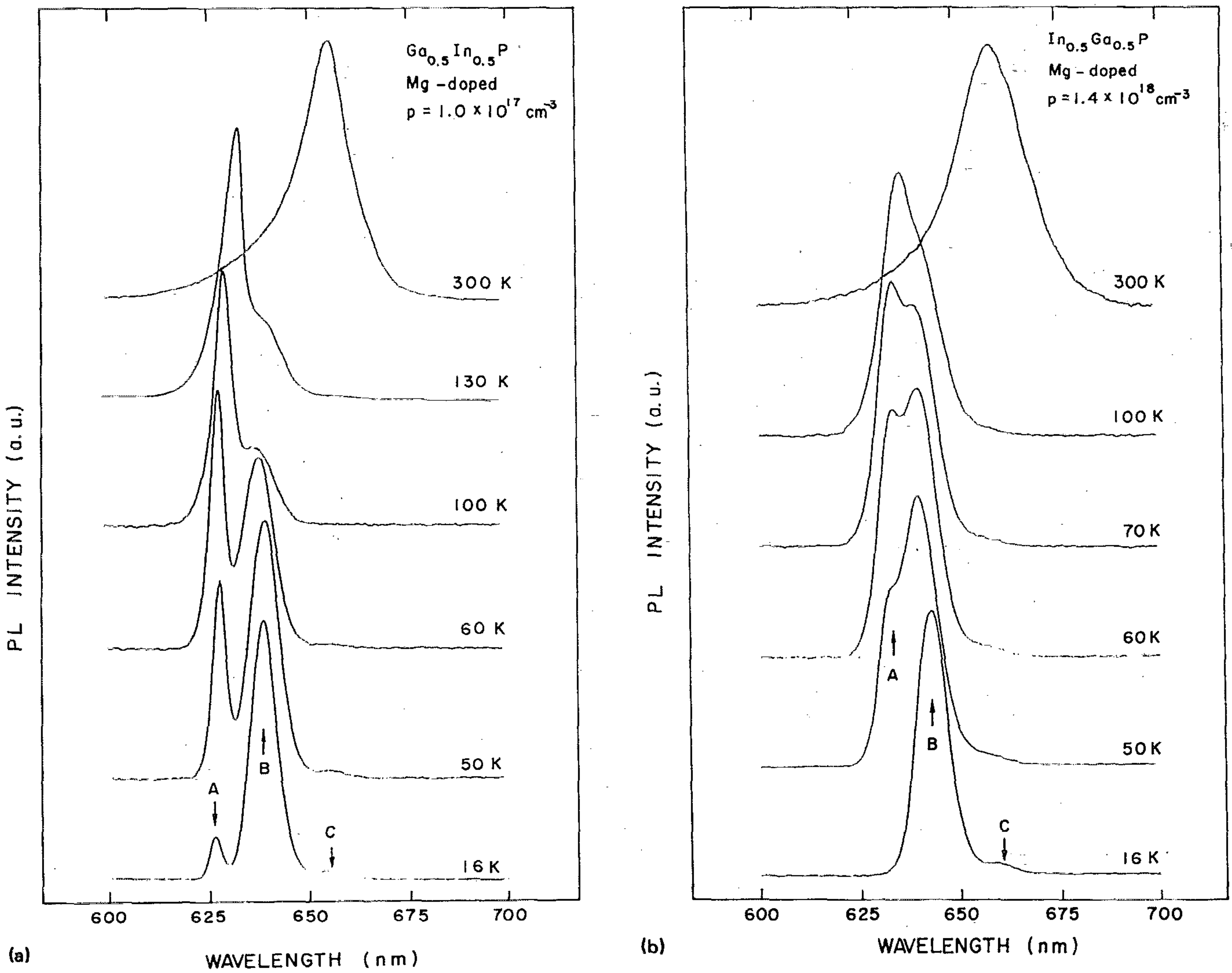

FIG. 2. Photoluminescence spectra of the Mg-doped $In_{0.5}Ga_{0.5}P$ layers with (a) $p = 1.0 \times 10^{17}$ cm^{-3} and (b) $p = 1.4 \times 10^{18}$ cm^{-3} at various temperatures between 16 and 300 K showing the gradual evolution of the peaks. The spectra are normalized to the same main peak intensity.

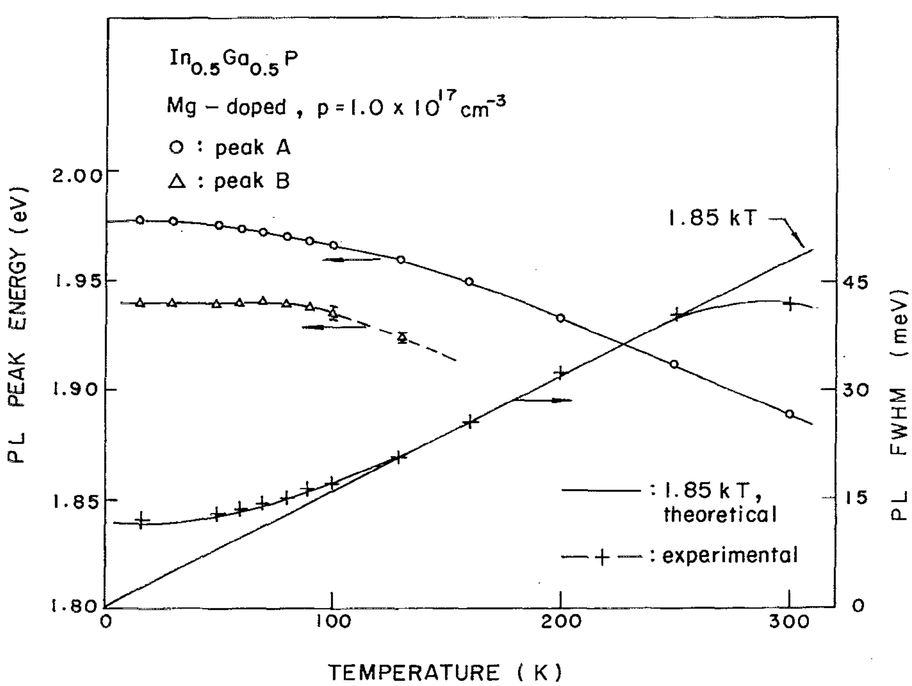

FIG. 3. Variation of the photon energies of the peaks A and B as a function of temperature for sample No. 2 with PL spectra as shown in Fig. 2 (a).

where $Eg(0)$ is the energy gap at 0 K, α and β are material constants. The calculated $Eg(0)$, α, and β by least-square method are 1.976 eV, 7.5×10^{-4} eV/K, and 500 K, respectively. Temperature dependence of the FWHM of peak A is also shown in Fig. 3. The experimental value agrees well with the theoretical value of 1.85 kT (Ref. 17) as shown in Fig. 3, where k is the Boltzmann constant. The slightly smaller FWHM than the theoretical value at 300 K seems to be due to reabsorption of emitted photons with energies higher than the peak energy by the epitaxial layer,[18] while the somewhat larger FWHM at the temperatures lower than 100 K may be due to the existence of another radiative transition process such as (residual) donor-to-valence-band recombination very near to the band-to-band transition peak.

IV. CONCLUSIONS

We have demonstrated the temperature dependence of photoluminescence of Mg-doped $In_{0.5}Ga_{0.5}P$ material with carrier concentrations of 1.0×10^{17}–7.0×10^{18} cm^{-3}. The relationship between the temperature and PL relative intensities of the two major peaks termed the intrinsic transition and band-to-acceptor recombination has been investigated in detail. At temperature above 60 K, the intrinsic recombination dominates in the doping range studied. The temperature dependence of band gap in $In_{0.5}Ga_{0.5}P$ layers determined from PL peak energy varies as $1.976 - [7.5\times10^{-4}T^2/(T+500)]$ eV.

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[1] R. J. Archer, J. Electron. Mater. **1**, 1 (1972).
[2] I. Ohta, M. Kazumura, and I. Teramoto, in *Gallium Arsenide and Related Compounds*, 1982 (Institute of Physics Conf. Series No.63), edited by T. Sugano (Oiso Japan, 1981), pp. 59–64.
[3] Y. K. Su, M. C. Wu, C. Y. Chang, and K. Y. Cheng, J. Appl. Phys. **62**, 2541 (1987).
[4] K. Oe, S. Ando, and H. Asai, J. Cryst. Growth **66**, 309 (1984).
[5] S. C. Lu, M. C. Wu, C. Y. Lee, and Y. C. Yang, J. Appl. Phys. **69**, 481 (1991).
[6] B. I. Boltaks, T. D. Dzhafarov, Yu. P. Demakov, and I. E. Maronchuk, Sov. Phys. Semicond. **9**, 545 (1975).
[7] C. R. Lewis, W. T. Dietze, and M. J. Ludowise, Electron. Lett. **18**, 569 (1982).
[8] W. D. Laidig, N. Holonyak, Jr., M. D. Camras, K. Hess, J. J. Coleman, P. D. Dapkus, and J. Bardeen, Appl. Phys. Lett. **38**, 776 (1981).
[9] I. Hino, A. Gomyo, S. Kawata, K. Kobayashi, and T. Suzuki, in *Gallium Arsenide and Related Compounds*, 1986 (Institute of Physics Conf. Series No. 79), edited by M. Fujimoto (Karuizawa, Japan, 1985), pp. 151–156.
[10] T. Suzuki, A. Gomyo, I. Hino, K. Kobayashi, S. Kawata, and S. Iijima, Jpn. J. Appl. Phys. **27**, L1549 (1988).
[11] L. B. Chang, K. Y. Cheng, and C. C. Liu, J. Appl. Phys. **64**, 1116 (1988).
[12] D. M. Eagles, J. Phys. Chem. Solids **16**, 76 (1960).
[13] C. J. Nuese, A. G. Sigai, M. S. Abrahams, and J. J. Gannon, J. Electrochem. Soc. **120**, 956 (1973).
[14] H. Kressel, C. J. Nuese, and I. Ladany, J. Appl. Phys. **44**, 3266 (1973).
[15] M. C. Wu, Y. K. Su, C. Y. Chang, and K. Y. Cheng, J. Appl. Phys. **58**, 4317 (1985).
[16] Y. P. Varshni, Physica **34**, 149 (1967).
[17] H. Barry Bebb and E. W. Williams, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1972), Vol. 8, p. 238.
[18] A. Suzuki, H. Kyuragi, S. Matsumura, and H. Matsunami, Jpn. J. Appl. Phys. **19**, L207 (1980).